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17.5% p-Type Silicon Heterojunction Solar Cells with HWCVD a-Si:H as the Emitter and Back Contact

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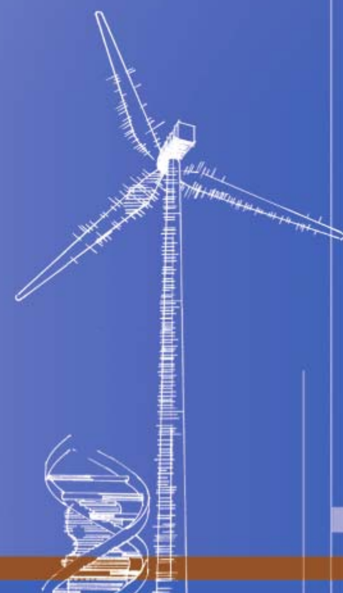

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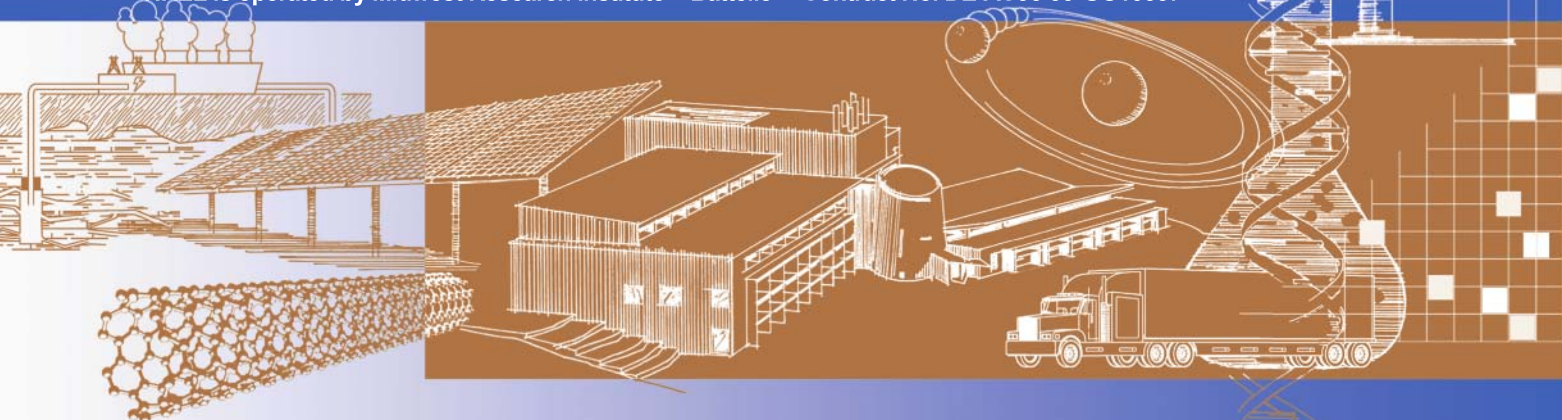

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ABSTRACT

Thin hydrogenated amorphous silicon (a-Si:H) layers deposited by hot-wire chemical vapor deposition (HWCVD) are used as both emitters and back contacts in silicon heterojunction solar cells. Low interface recombination velocity and high open-circuit voltage are achieved by a low substrate temperature (<150°C) intrinsic a-Si:H deposition which ensures immediate amorphous silicon deposition. This is followed by deposition of doped a-Si:H at a higher temperature (>200°C) which appears to improve dopant activation. With an i/n a-Si:H emitter, we obtain a confirmed efficiency of 17.1% on textured p-type float-zone (FZ) silicon with a screen-printed aluminum back-surface-field (Al-BSF) contact. Employing a-Si:H as both the front emitter and the back contact, we achieve a confirmed efficiency of 17.5%, the highest reported efficiency for a p-type c-Si based heterojunction solar cell.

1. Introduction

The silicon heterojunction (SHJ) is one of the most attractive device structures for fabrication of high-efficiency silicon solar cells at low temperatures (<250ºC) with simple processing. The excellent surface passivation provided by H and extra band bending due to the larger band gap of a-Si:H compared to c-Si makes well-designed a-Si:H emitters superior to conventional emitters made by dopant diffusion. Furthermore, a thin layer of a-Si:H, doped the same as the base wafer provides a back collector with very effective back-surface field that reduces the recombination velocity. The current conduction through the a-Si:H collector is adequate and no localized current conduction windows are needed, in contrast to dielectric back-surface passivation layers. These outstanding properties open the path to many a-Si/c-Si heterojunction silicon solar cell designs, the most successful being the Sanyo HIT cell [1] employing plasma-enhanced chemical vapor deposition (PECVD) to deposit thin p/i (emitter) and n/i (collector) a-Si:H layers on n-type wafers.

Great care must be taken in using PECVD to make high-efficiency SHJ cells because of the potential for plasma damage to the c-Si wafer surfaces. At NREL, hot-wire chemical vapor deposition (HWCVD) is used to eliminate the possibility of such ion damage. We have successfully used this technique to obtain record efficiencies for p-type silicon-wafer based heterojunction solar cells.

2 Results and Discussions

2.1 Single-Heterojunction SHJ Solar Cells – the a-Si:H Emitter

We use a standard Al-BSF on the back to optimize the a-Si:H emitter on the front. In a typical a-Si:H/c-Si heterojunction solar cell, a thin (~4 nm) intrinsic hydrogenated a-Si:H layer is interposed between the base wafer and the heavily doped emitter. Though such thin i-layers are difficult to characterize, i-layers likely have a far lower density of defects and a slightly larger energy gap than doped a-Si:H layers: both factors are advantageous for reducing dark current through the junction and increasing V_{oc}. If inadvertent epitaxy occurs during the i-layer deposition, it is unlikely to be of high quality. Further, if crystallinity extends through the i-layer, the rough c-Si interface can be contacted in places by the doped a-Si:H which is likely a less effective passivant than the i-layer. Any dark-current path through inadequately passivated interface states in a heterojunction solar cell reduces the open-circuit voltage (V_{oc}). Using HWCVD, we vary both the i- and n-layer deposition temperatures (T_d) to find the optimum conditions. It turns out that high V_{oc} values with (100) silicon wafers are obtained at temperatures below 150°C, but at temperatures higher than 200°C, V_{oc} is much reduced. This is because epitaxy is usually favored at i-layer deposition temperature T_d > 200°C while lower temperature (T_d < 150°C) ensures abrupt a-Si:H deposition [2].

With an i-layer deposited at a low temperature of 100°C, we find that raising the n-layer deposition temperature to about 200°C provides the highest V_{oc} (see Figure 1). This seems to provide effective activation of the phosphorous dopant and a better quality n-layer. These optimizations on the a-Si:H emitter lead to 17.1% efficient single-side SHJ solar cells as shown in Table 1. This is a record for p-type c-Si based heterojunction solar cell using an Al back-surface field contact.

Table 1. Confirmed measurements of 1-cm^2 ITO/a-Si:H/c-Si/Al-BSF single-side solar cells on p-type c-Si substrates

ID	V_{oc}(V)	J_{sc}(mA/cm^2)	F.F.(%)	η(%)	Substrate
16C	0.645	33.11	79.2	16.9	1.0 Ω·cm planar FZ
65C	0.652	32.16	80.5	16.9	0.5 Ω·cm planar FZ
62A	0.636	34.96	76.8	17.1	1.0 Ω·cm textured FZ

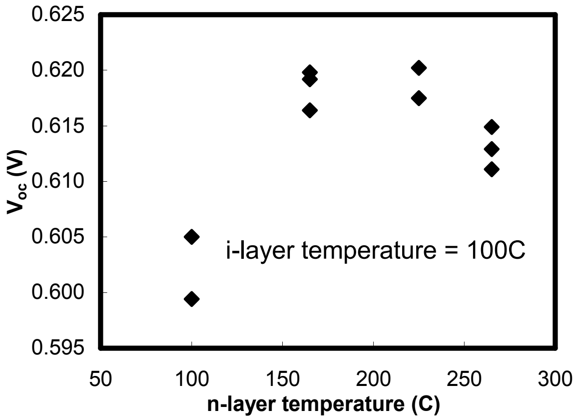

Fig. 1. Effect of n-layer deposition temperature on V_{oc}.

2.2 Double-Heterojunction SHJ Solar Cells – the a-Si:H Back Contact

Applying the best emitter a-Si:H deposition conditions to the backside passivation, we have fabricated simple double-heterojunction SHJ solar cells with a structure of ITO/a-Si:H emitter/c-Si/a-Si:H back contact.

Table 2. Effects of a-Si:H as emitter and back contact on V_{oc}

ID	V_{oc} (V)	Structure
5-5	0.63	diffused n+/planar p-FZ/Al-BSF
16C	0.65	a-Si(n/i)/planar p-FZ/Al-BSF
1540	0.65	a-Si(n/i)/textured p-FZ/Al-BSF
2933	0.66	a-Si(n/i)/textured p-FZ/a-Si(i/p)
2930	0.69	a-Si(p/i)/planar n-FZ/a-Si(i/n)

Table 2 illustrates the successive increases in V_{oc} by replacing a diffused junction with an a-Si:H emitter on the front and replacing an Al-BSF with an a-Si:H contact on the back. On textured 1.3 Ω·cm p-type FZ-Si, with an a-Si:H(i/p) back contact and a-Si(i/n) emitter, a V_{oc} of 0.66 V is obtained. Clearly, a-Si:H(i/p) contributes a stronger back-surface field than Al, without introducing problems in current collection. On planar 2.0 Ω·cm n-type FZ-Si, we obtain an even higher V_{oc} of 0.69 V. Of particular importance is that V_{oc} does not suffer from using a textured surface compared to a planar substrate. Using a textured bare FZ-Si wafer, we obtain a confirmed efficiency of 17.5% (see Figure 2), the highest reported for a p-type c-Si based heterojunction solar cell.

3 Conclusions

Effective a-Si:H/c-Si heterointerfaces with minimal recombination loss can be obtained using HWCVD. Abrupt a-Si:H(i) deposition and a flat hetero-interface to the c-Si substrate achieved at low-temperature (<150°C) ensures that the a-Si:H contacts high quality c-Si with low interface defect density and high band bending while minimizing the a-Si:H/c-Si interface area. A higher temperature (~200°C) deposition of the subsequent doped layer enhances the interface passivation and the built-in voltage, likely by activating dopants and reducing defect density in both the underlying i- and the doped-layer. When HWCVD a-Si:H is used as the back collector, a highly effective back-surface field is demonstrated by double-heterojunction SHJ devices with preliminary V_{oc} values of 691 mV and 660 mV on planar n-type FZ-Si and on textured p-type FZ-Si, respectively.

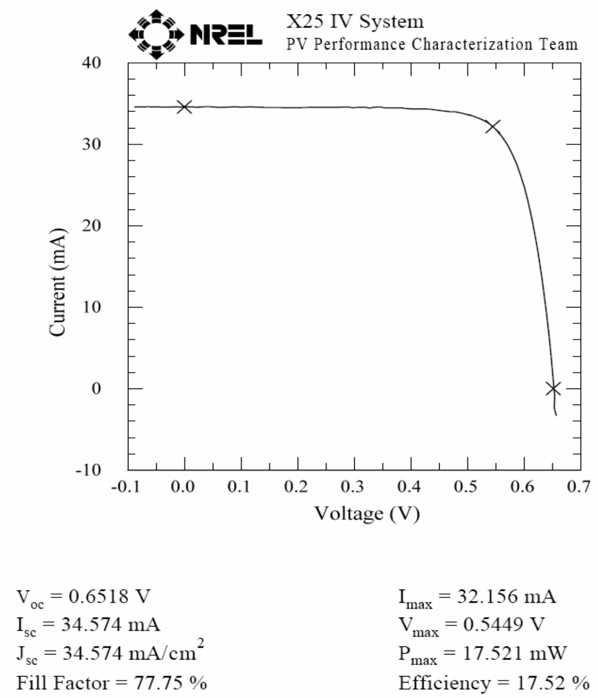

Fig. 2. IV-curve of the 1-cm^2 double-heterojunction cell.

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